Effects of Vegetation and of Heat and Vapor Fluxes from Soil on Snowpack Evolution and Radiobrightness

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***Abstract*—The radiobrightness of a snowpack is strongly linked to the snow moisture content profile, to the point that the only operational inversion algorithms require dry snow. Forward dynamic models do not include the effects of freezing and thawing of the soil beneath the snowpack and the effect of vegetation within the snow or above the snow. To get a more realistic description of the evolution of the snowpack, we reported an addition to the Snow-Soil-Vegetation-Atmosphere-Transfer (SSVAT) model, wherein we coupled soil processes of the Land Surface Process (LSP) model with the snow model SNTHERM. In the near future we will be adding a radiobrightness prediction based on the modeled moisture, temperature and snow grain size profiles.**

The initial investigations with this SSVAT for a late winter and early spring snow pack indicate that soil processes warm the snowpack and the soil. Vapor diffusion needs to be considered whenever the ground is thawed. In the early spring, heat flow from the ground into a snow and a strong temperature gradient across the snow lead to thermal convection. The buried vegetation can be ignored for a late winter snow pack. The warmer surface snow temperature will affect radiobrightness since it is most sensitive to snow surface characteristics. Comparison to data shows that SSVAT provides a more realistic representation of the temperature and moisture profiles in the snowpack and its underlying soil than SNTHERM.

The radiobrightness module will be optimized for the prediction of brightness when the snow is moist. The liquid water content of snow causes considerable absorption compared to dry snow, and so longer wavelengths are likely to be most revealing as to the state of a moist snowpack. For volumetric moisture contents below about 7% (the pendular regime), the water forms rings around the contact points between snow grains. Electrostatic modeling of these pendular rings shows that the absorption of these rings is significantly higher than a sphere of the same volume. The first implementation of the radiobrightness module will therefore be a simple radiative transfer model without scattering.

Keywords- snow; soil; radiobrightness

I. Introduction

Changes in the permafrost and snowcover in cold regions are of profound importance for our earth. Furthering knowledge about the impact of snowmelt and understanding how snowmelt will interact with climate change and other environmental stresses, such as pollution and habitat fragmentation, are important areas of inquiry.

SNTHERM is a high physical fidelity snow model [1,2], but it uses a simple soil model that does not include many of the energy and moisture transport processes common to soils. The Land Surface Process (LSP), a high physical fidelity soil model [3,4], has been combined with the snow pack of SNTHERM, to create the Soil-Snow-Atmosphere Transfer (SSAT) model [5]. Based on SSAT, a new model called Soil-Snow-Vegetation-Atmosphere Transfer (SSVAT) has been developed. SSVAT couples the vegetation modules in LSP with SSAT to consider interactions between air, vegetation, snow and soil. A future radiobrightness module will be developed for the prediction of brightness when the snow is moist.

II. SSVAT Model

SSVAT is a coupled model which includes a snow model, SNHTERM and a soil model, LSP. Assuming a one-dimensional snow pack, flow is perpendicular to the layering and snow processes change only with depth. The volume of soil was assumed constant so frost heave was not considered in this version of model.

A. Air/Snow Interface and Fluxes within the Snow Pack

Energy fluxes at the upper boundary will affect the temperature of the snowpack and soil, which will in turn affect the thawing and freezing of the snow pack and soil. Sublimation/condensation, precipitation, water flow, and ponding are responsible for the mass transfer of the snow pack surface, thus increasing or reducing the mass of the snow pack. The heat and moisture fluxes within the snow pack are governed by coupled differential equations. SSVAT uses the same algorithms for these processes as SNTHERM.

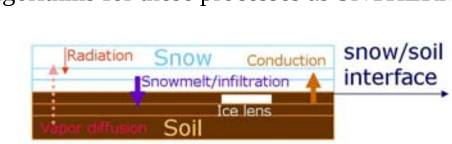

Figure 1. Processes at the snow/soil interface.

B. Snow/Soil Interface

The energy fluxes at the snow/soil interface include vapor diffusion and geothermal heat from the soil that warm the snowpack. If the snowpack is thin, solar radiation may penetrate the snowpack and warm the soil. These processes are shown in Fig 1.

Precipitation, snowmelt and ponded water will flow through the snowpack. Water flow from the snowpack may infiltrate the frozen soil or freeze the thawed soil, forming ice lenses near the surface soil. Assuming the depth of ponding is very thin, the infiltration rate for surface soil is estimated using simplified form of Philip's transient infiltration equation [6,7]. The mass and energy at the snow/soil interface should be adjusted to be the upper boundary of the mass and energy transfer for soil.

C. Heat and Moisture Transfer within the Soil

SSVAT uses the same sensible and latent heat flux algorithms as in LSP. The heat fluxes in the soil include water flow, vapor diffusion, and thermal conduction. The moisture fluxes for the soil include gravity flow, physical adsorption, and capillary condensation [4].

D. Canopy Snow Processes

As forest litter accumulates, the pure snow surface is being "polluted" and the subcanopy snow albedo is reduced. The fractional coverage of litter in or on the snowpack is assumed to increase throughout the entire snow season and estimated from a semi-empirical formula. Snow albedo beneath the forest cover and litter fall can be estimated as a function of the fractional coverage of litter [8].

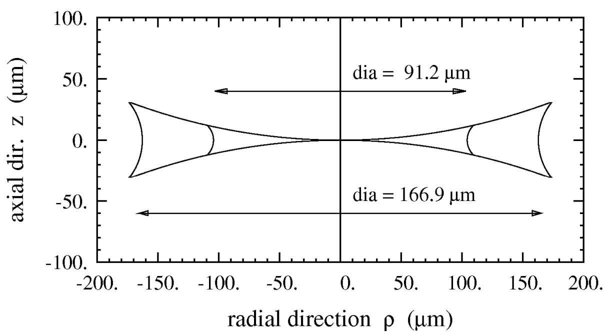

Figure 2. Cross sectional shapes of liquid water forming between touching spherical ice particles of 1mm diameter. The equivalent diameter of a sphere of the same volume is shown for each pendular ring.

E. Radiobrightness Module

The radiobrightness module is under development. Our efforts will focus on characterization of moist snowpack since significant progress has been made on the emission from dry snow packs [9]. Liquid water in the snowpack accumulates at the contact points between snow particles, forming pendular rings similar to those shown in cross section in Fig. 2. These rings are small with respect to a wavelength, even at 37GHz, and so the absorption dominates scattering from these particles [10]. The absorption and scattering from these particles has been modeled using the program DIELCOM [11], which finds the electrostatic polarizability tensor of arbitrary bodies-of-rotation and arbitrary dielectric.The absorption cross section for isotropically distributed pendular rings exceed that for an equal volume sphere, as shown in Fig. 3. Furthermore, the geometry of these rings is such that rate of increase in absorption cross section with volume is smaller for the rings than for spheres. This is consistent with the observation that only a small amount of liquid water in the snow pack is needed to transform a dry, scattering snow pack into a wet, absorbing snow pack [12]. This pendular ring concept will be the basis for absorption and scattering in the moist snow pack radiobrightness module.

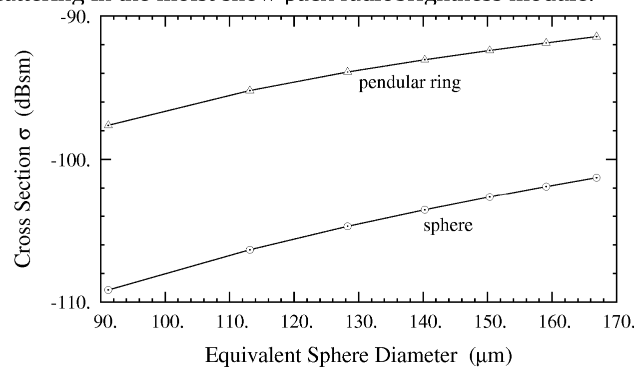

Figure 3. Absorption cross sections of randomly oriented pendular rings and spheres of the same volume.

III. SSVAT MODEL PREDICTIONS

Measurements made at the Local Scale Observation Site (LSOS) of the Cold Land Processes Experiment (CLPX) in northern Colorado are used to drive the SSVAT and SNTHERM models, and to validate the model outputs. The LSOS is a 100 m x 100 m study site located within the Fraser ISA. Data were collected during late winter and early spring. These periods, especially for spring, were selected because the surface properties (albedo, roughness length, insulation, etc.) can change significantly, thereby affecting temperatures, moistures and fluxes. Our data set and other meteorological and snow data sets include soil temperature profiles, soil moisture profiles, soil heat flux profiles, snow temperature profiles, radiative fluxes, air temperature and relative humidity measurements [13-18]. Snow pit measurements and micrometeorological data on DOY 50-54 (late winter) and DOY 84-88 (early spring) gave density of water, temperature and grain size profiles for initialization and validation for two 5-day simulations.

A. Effects of a Thatch Layer

Thatch fraction at the snow/soil interface was adjusted from 0 to 90% in repeated 14-day simulations. The results show that the temperature profiles did not change throughout the 14-day simulation when the litter fraction at the snow/soil interface varied (Fig. 4 only shows temperature profiles). The thatch layer above the soil did not affect moisture, temperature profiles of either snow or soil, or snow grain size profiles. This study suggests that a thatch layer at the snow/soil interface, buried within the snow, has no significant effect on the snow or soil characteristics.

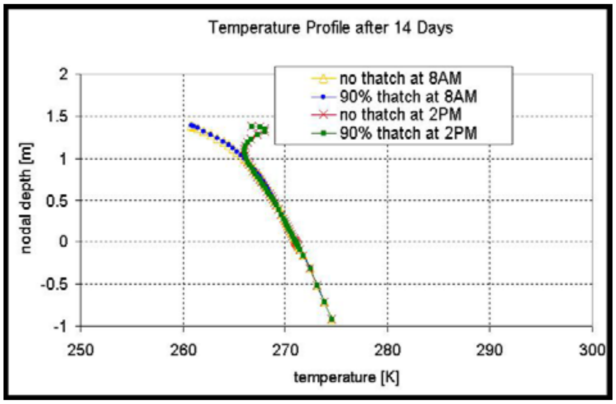

Figure 4. Simulated temperature profiles with no thatch and with thatch volume fractions of 90% by volume. Thatch does not affect the temperature, grain sizes, or moisture in the snow pack.

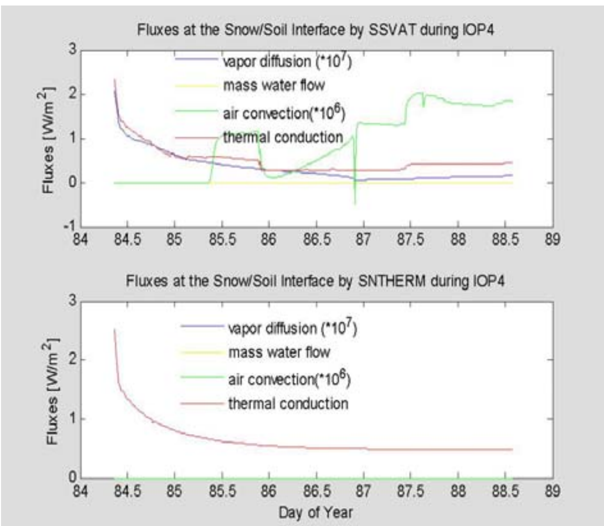

Figure 5. Simulated fluxes at the snow/soil interface at CLPX.

B. Simulation of Fluxes at the Snow/Soil Interface

The SSVAT model predicts the heat transport across the snow/soil interface to include significant vapor diffusion and thermal conduction in the late winter. Free convection of air within the snow was an additional heat flux found in the SSVAT predictions in the early spring, shown in Fig. 5, while the heat transport predicted by SNTHERM only includes the thermal conduction since SNTHERM simplifies the soil processes. This study suggests that the vapor diffusion needs to be considered in both late winter and early spring. Also, in early spring, depth hoar may occur and permit natural convection of air in the snow, driven by thermal gradients. Heat flows from the ground into the snow and extremely low air temperatures produce a strong temperature gradient across the snow, with warm buoyant air at the base of the snow and cold dense air at the top. This unstable stratification leads to thermal convection. This results in a warmer snow and soil temperature and larger snow grain size, including further development of depth hoar.

C. Validation of Temperature Profiles

The SSVAT predictions of snow pack temperature profiles are a better match to the observations than those of SNTHERM. After 5-day simulations, the SSVAT model predicts up to 1.4K warmer snow pack than SNTHERM on DOY 54 (Fig. 6a), and up to 3.2K warmer on DOY 88 (Fig. 6b). This latter example shows that the temperature predictions for two models were significantly different near the snow surface in the early spring despite the fact that the models only differ at the snow/soil boundary and below. The temperature in the upper snow pack can be affected by the soil processes even when the soil and lower snow pack temperature predictions by two models are similar.

This study suggests SSVAT provides a more realistic representation of the state of the snow pack and its underlying soil. The manifestation of soil processes at the air/snow surface will affect the radiobrightness because it is most sensitive to snow surface characteristics.

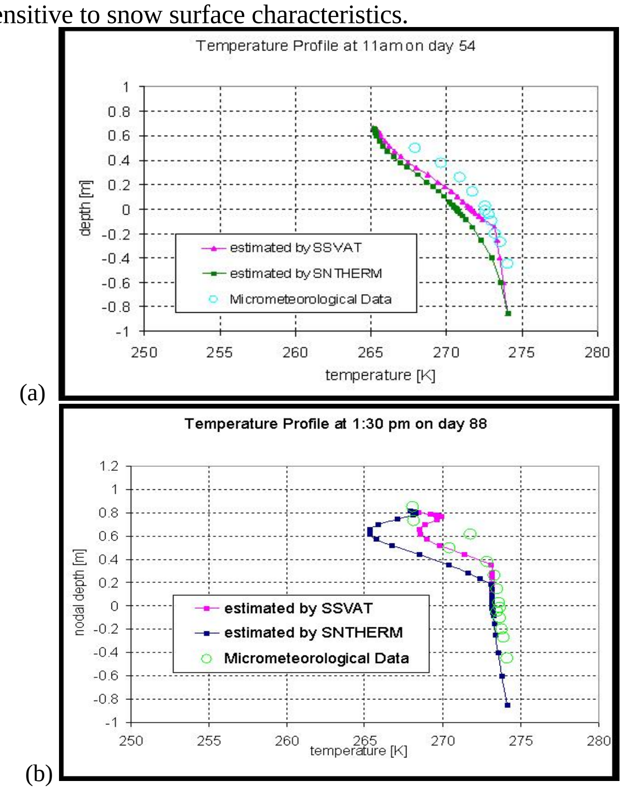

Figure 6. Temperature profiles predicted by SSVAT and SNTHERM, and measured temperature profiles. Even though the two models use the same algorithms above the snow soil boundary, the inclusion of soil processes in SSVAT improves its performance even near the surface.

D. Validation of Water Density Profiles

Fig. 7 shows that the predictions of the density of water for the two models were different in the upper soil since SNTHERM artificially drains the water at the snow/soil interface. There were no significant differences in the density of water profiles in the snow because SSVAT uses the algorithms in SNTHERM.

SSVAT predicted water density well in the late winter. SNTHERM did not estimate the variation of the soil water density. This suggests that the SSVAT provides a more realistic representation of the distribution of moisture profiles. There were also no significant differences between the model predictions in the deeper soil since the deeper soil moisture did not vary significantly.

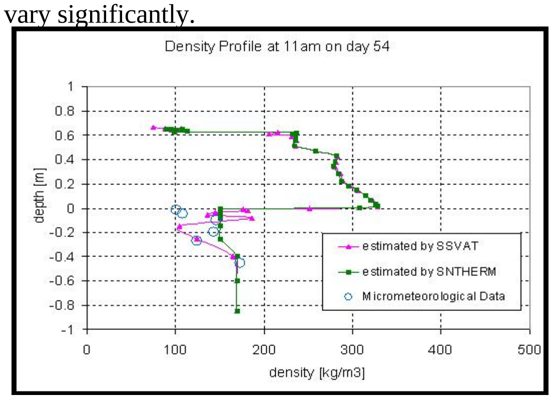

Figure 7. Moisture density predictions and measurements in late winter. The SSVAT predictions capture the variations in moisture in the shallow soil.

E. Grain Size Profiles

Snow grain size values were larger in our snow model, SSVAT, because the soil processes allow the vapor fluxes across the interface that favors grain growth (Fig 8). The increasing thermal fluxes predicted by SSVAT are the cause of the larger grain size profiles.

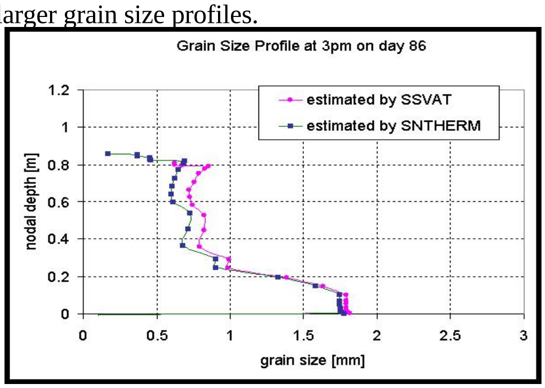

Figure 8. Snow grain size predictions of SSVAT and SNTHERM.

IV. CONCLUSIONS

The SSVAT model for snow pack evolution is introduced. The SSVAT uses the snow pack algorithms of SNTHERM, but links them to the soil processes of LSP, and includes vegetation within the snow pack. SSVAT simulations indicate that (1) the buried vegetation at the snow/soil interface can be ignored for a late winter snow pack, (2) vapor diffusion needs to be considered in both late winter and early spring, and (3) convection of air in snow may occur in the early spring, enabled by the evolution of depth hoar and driven by nighttime thermal gradients. The SSVAT model predicts warmer snow and soil temperatures and larger snow grain sizes than SNTHERM predicts.

Comparison of the model predictions to measurements indicates that SSVAT provides a realistic representation of the distribution of temperature and moisture profiles in the snowpack and its underlying soil. The coupling of soil processes from LSP with SNTHERM make a significant improvement to the model predictions over that of SNTHERM alone. Differences in the predictions of the snow state can be seen throughout the snow pack, even at the surface, where radiobrightness is most affected.

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